GUIDANCE AND CONTROL IN SUPERCIRCULAR ATMOSPHERE ENTRY

by Rodney C. Wingrove
Research Scientist
NASA, Ames Research Center
Moffett Field, California

ABSTRACT

This paper discusses planetary entry maneuvers which include atmospheric capture for Mars entry velocities up to 12 km/sec; atmospheric capture for Earth entry velocities up to 21 km/sec; skip-out control to either a parking orbit or extended ranges; and terminal range control. Simulator results are compared for both automatic and piloted-guidance systems. The results are presented to illustrate the expected guidance performance as compared with the vehicle's full capabilities. Several factors considered are the control response requirements, the effect of measurement errors and atmosphere uncertainties, and the effect of various display and control techniques.

INTRODUCTION

With the successful entries of manned vehicles from near Earth orbits, attention has been turned to the problems of atmosphere entry for more advanced manned space-flight missions. Manned trips to the planets have been studied in a number of recent investigations.[1-13] Studies have shown that vehicles returning to Earth from these missions will enter the atmosphere at speeds of up to 15 km/sec and perhaps as high as 20 km/sec. Entry velocities at a planet such as Mars are expected to be as high as 12 km/sec. Retrorockets could conceivably reduce these large approach speeds, but the weight of fuel required makes this method of braking impractical, and we are led to aerodynamic braking in the atmosphere as the most realizable solution at this time.

During aerobraking maneuvers, manned vehicles must be able to control aerodynamic lift to satisfy several requirements. Initially on entering the atmosphere, the vehicle must perform a "capture" maneuver to keep from exceeding acceleration limits or skipping back out of the atmosphere. After the capture maneuver and during the supercircular deceleration portion of the flight, the control system must regulate a large negative aerodynamic lift force to counteract the centrifugal force of the trajectory, and thus keep the vehicle within the planetary atmosphere. To maneuver the vehicle to the planet surface or to a parking orbit, the control system must determine the appropriate lift force. Throughout the flight the vehicle heating and acceleration loads must be kept within tolerable limits by the control system. This system must be able to perform adequately even though there are errors in the measuring instruments and uncertainties in the atmosphere characteristics.

In previous studies[14-29] the control of space vehicles entering the Earth's atmosphere from circular or near circular velocities have been analyzed. In this paper these studies are extended to the entry control problems associated with planetary missions. This paper will first consider the basic dynamics of the entry trajectories and how the dynamics of the trajectory variables are related to the guidance and control problem at the extreme entry velocities. Simulator results will be presented that illustrate control in the capture maneuvers, control during skip out to either a parking orbit or to extended ranges, and control to the planet's surface. A comparison will be made of the control problems at both Earth and Mars. The discussion will cover both the use of automatic control and manual back-up control systems.

TRAJECTORY CONSIDERATIONS IN PLANETARY ENTRIES

Trajectory Dynamics

A space vehicle approaching a planet at supercircular velocity must be within a safe entry corridor if it is to be captured within the planet's atmosphere. The entry corridor, illustrated in Fig. 1, is the difference in height of the vacuum perigees of two conic trajectories,[13] the upper trajectory forming the overshoot boundary and the lower trajectory being the undershoot boundary. If the vehicle approaches above the overshoot trajectory, it does not enter the atmosphere sufficiently to be captured; if it approaches below the undershoot trajectory, its total acceleration force will exceed a specified value (usually considered 10g).

After the vehicle has entered the atmosphere, aerodynamic lift control must be correctly applied to insure that the vehicle will not unintentionally skip back out of the atmosphere. In this capture maneuver a negative aerodynamic lift force, centrifugal force, and gravity force must essentially balance along the trajectory

Superior numbers refer to similarly-numbered references at the end of this paper.

(i.e., equilibrium glide). The stability of vehicle motions near equilibrium flight can be illustrated by the trajectories of a vehicle trimmed at a constant lift/drag ratio. Fig. 2 presents trajectories of a constant L/D vehicle entering the Earth's atmosphere at subcircular and at supercircular entry velocities. The altitude along the trajectories is presented as a function of $\bar{V}$, the ratio of total velocity to local circular velocity. The example trajectories are for a vehicle entering the Earth's atmosphere at an altitude of 100 km where the sensible atmosphere begins. For entry at near circular velocity ($\bar{V}_i = 1$) the vehicle is shown entering with positive lift which allows it to maintain near equilibrium flight. We see these subcircular dynamics are dynamically stable about the equilibrium glide path; that is, the motions are oscillatory and there is a small amount of damping. For the vehicle entering at extreme supercircular velocity ($\bar{V}_i = 2.7$) negative lift is used to maintain near equilibrium flight; however, here we see the dynamics are unstable. One supercircular trajectory is shown to skip back out of the atmosphere, while the other trajectory with just a small change in entry conditions dives deeper into the atmosphere. These uncontrolled dynamics are studied further in detail in references 30 to 32 where they are considered analogous to the classical aircraft phugoid motions.

The data in Fig. 2 show that the phugoid dynamics expected in supercircular entries are unstable and thus illustrate the need for control. This control is critical, and fast response is needed for extreme Earth entry velocity where the time to double amplitude of the uncontrolled dynamics can be on the order of 5 seconds. At Mars the supercircular phugoid dynamics are somewhat more stable than at Earth because the gravitational force is less; therefore less lift is required to hold the vehicle near equilibrium lift.

Now we can point out in Fig. 2 the boundaries within which the vehicle must operate. If the vehicle is near equilibrium flight and is allowed to fly above the supercircular equilibrium glide path, it will skip back out of the atmosphere uncontrolled. The allowable region of flight must be below this equilibrium flight boundary. On the other hand, the vehicle cannot be allowed to dive too far into the atmosphere or the acceleration forces will be greater than 10g. During the supercircular portion of the entry, the vehicle must be flown between the upper skip-out boundary and this lower acceleration boundary.

Relationship of Control and Dynamics

The method of trajectory control most commonly considered for entry at supercircular speeds is to use the roll angle of the vehicle to regulate the vertical component of the lift vector. With this control method, which shall be considered in this paper, it is assumed that the vehicle maintains nearly a constant aerodynamic trim condition about the pitch and yaw axis.

Fig. 3 is a simplified block diagram showing the relationship between vehicle roll control and the trajectory dynamics. This diagram depicts altitude and range variations in only the vertical plane. Crossrange control will be illustrated later in the paper. This figure illustrates the chain of events that result when a roll control moment is applied by the reaction jets. The torque about the roll axis produced by the roll control jets is integrated to produce a roll rate. Integrating the roll rate changes the roll angle. The control of the roll angle is a part of the vehicle "short-period dynamics." The dynamic response of the system which follows a change in roll angle is termed the "long-period" or trajectory dynamics.

The roll angle determines the component of the aerodynamic lift force vector in the vertical plane. The integrated changes in this vertical lift force determine the changes in the vehicle rate of climb. Integrating this vertical velocity determines the changes in the vehicle altitude and consequently the changes in drag acceleration. The subsequent integration of drag acceleration determines changes in horizontal velocity, and a final integration determines the subsequent changes in the downrange.

Fig. 3 illustrates that guiding to a given downrange point is, in effect, controlling a sixth-order function. With an on-board computer and inertial platform, position and velocity information can be accurately determined during entry, and guidance logic equations within the computer can determine the proper roll angle required to capture the vehicle and to reach the destination. Several types of guidance logic equations that can be programmed in the on-board computer have been found to be satisfactory for supercircular entries. These programs include the use of fast-time predicted paths[14,15,21-23,29] as well as stored path information.[16-20,23] In the present paper, automatic control results will be illustrated by the fast-time prediction method outlined in reference 29.

TRAJECTORY CONTROL IN PLANETARY ENTRIES

The results presented were obtained from simulation studies of automatic and manual back-up systems.[27,29] The control problem of capture within the atmospheres of Earth and Mars will be discussed first. Next, skip-out control to either a parking orbit or to extended ranges will be considered, and, finally, the terminal range control to the planet's surface.

Capture Control

The control required in capture for the extreme Earth entry velocity is illustrated in Fig. 4 for entries near the overshoot boundary and near the 10g undershoot boundary. These data were obtained using the automatic control method outlined in reference 29. At the overshoot boundary the vehicle lift is held full down throughout the initial maneuver to insure that the vehicle is pulled down into the atmosphere. When the peak acceleration is reached, the roll angle is modulated to stabilize the trajectory about equilibrium and to maneuver onto the desired path. Near the undershoot boundary the full positive lift is held initially to insure that the acceleration will stay within 10g. Near peak acceleration the vehicle must be rolled to that negative lift required to maintain equilibrium and keep the vehicle from skipping back out of the atmosphere. The roll angle is then modulated to stabilize the trajectory about equilibrium and to maneuver onto the desired path.

The proper timing of this roll maneuver for the undershoot boundary case is critical at the higher entry velocities. This is illustrated in Fig. 5 for entries at both Earth and Mars. These data are for representative vehicles with a maximum roll rate of 20°/sec. For the extreme Earth entry velocity there is approximately a 1-second time leeway within which the roll-over maneuver may be initiated. If the roll maneuver is initiated later than this the vehicle will skip back out of the atmosphere. Control applied earlier than this time will cause the vehicle to exceed 10g acceleration. For the extreme entry velocity at Mars, the roll maneuver is less critical and there is about a 6-second leeway within which the roll maneuver may be initiated.

For the capture maneuver in Earth entries it has been found that increasing the maximum roll rate capability of the vehicle from 20°/sec to even an infinite value will allow only about 1/2-second additional leeway for the maneuver. For roll rates less than about 15°/sec there is essentially no time leeway within which the roll maneuver can be performed with the acceleration peak less than 10g. It appears that a maximum roll rate of at least 20°/sec, which is on the order of that for the current Gemini and Apollo vehicles, is adequate to perform the capture maneuvers.

Proper control timing does not appear difficult with automatic control and a high-speed on-board computer.[29] The timing is very critical from the pilot's standpoint, though, if he must perform the entry with only minimal back-up display information. In this case the pilot must "play it safe" and roll a couple of seconds early to insure capture. The corridor capabilities of both the automatic and manual back-up control systems are compared in Fig. 6 with the maximum available corridors. These data are for representative entry vehicles both at Earth and Mars.

For an $L/D = 1$ vehicle entering the Earth's atmosphere at the extreme entry velocity of 21 km/sec ($\bar{V}_i \approx 2.7$) there is about a 15-km corridor. A 15-km corridor is on the order of that required to accommodate midcourse guidance errors and atmosphere uncertainties.[9,33] A vehicle with an $L/D = 0.5$ entering the atmosphere of Mars at a maximum expected velocity of 12 km/sec ($\bar{V}_i \approx 3.5$) will have an available corridor of about 30 km.

The manual control values shown in Fig. 6 were obtained from piloted simulation studies in which the pilot was only given the information that would be available from a back-up roll gyro and a single strapped down accelerometer.[29] The pilot found control to be more difficult in the Earth entry than in the Mars entry. This was due primarily to the critical roll timing required for capture and the more unstable control situation encountered in the Earth's atmosphere as compared to the Mars atmosphere. For the Mars entries the pilot was able to use essentially the full corridor capabilities of the vehicle beyond $\bar{V}_i = 3.5$, the maximum expected entry velocity. For Earth entries the pilot was able to control consistently within a 15-km corridor depth to about $\bar{V}_i = 2.5$. This compares with the full vehicle capability which gives a 15-km corridor at about $\bar{V}_i = 2.7$.

With an automatic system, as outlined in reference 29, vehicles can utilize most of their full corridor. This particular system uses feedback measurements of velocity, acceleration, and altitude rate. Possible errors in measuring the altitude rate have been found to be the most critical. For an Earth entry at $\bar{V}_i = 2.7$ this measurement must be accurate to within ±50 m/sec for the vehicle to utilize 99 percent of the available corridor and within ±90 m/sec to utilize 90 percent of the available corridor. In contrast, for entry to Mars at the extreme entry velocities, $\bar{V}_i = 3.5$, the altitude rate must be known to only about ±120 m/sec to utilize 99 percent of the available corridor.

The day-to-day uncertainties in the Earth's atmosphere do not appear to seriously affect the ability of the guidance systems to utilize the full corridor capabilities of the vehicle. However, we are not at all sure of what variations to expect in the Mars atmosphere. It appears that if the scale height of the atmosphere can be known within about ±25 percent, the vehicle can utilize the full corridor available at the particular time of entry.*

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*When the acceleration measurement is used in guidance logic, it is only an uncertainty in the scale height of the atmosphere density rather than in reference density level that will affect the capture control.

Skip-Out Control

When a vehicle approaches a planet at supercircular velocities it might be controlled to skip out of the atmosphere and into a parking orbit or possibly to extend range. The exit conditions for achieving the desired altitude or range objectives are illustrated in Fig. 7. These data are derived from Keplerian equations of motion for the extra-atmosphere portion of the flight. It can be seen that for the skip out to either a desired altitude or range there is a choice of the combinations of exit angles and exit velocities which will meet these objectives. The choice of exit condition and the manner in which the vehicle must be controlled to arrive at this condition will be discussed briefly. Representative examples will illustrate the skip-out control into a parking orbit about Mars, and the skip-out control to extend the range at Earth return.

Skip-out control to a parking orbit at Mars.- The use of aerodynamic braking to decelerate a spacecraft and establish an orbit about Mars has been considered in a number of studies.[1-12,34-38] The guidance within the atmosphere to reach the parking orbit consists in controlling the vehicle vertically to the desired maximum skip-out altitude and in controlling laterally through the desired plane angle change. A thrusting maneuver is needed then, near the maximum skip-out altitude to circularize the orbit. Only that portion of control within the atmosphere is discussed in this paper.

The choice of exit conditions to control depends on many considerations. These are typically: to minimize thrust required to inject into orbit; to minimize effects of measurement errors; to minimize effects of density uncertainties; to minimize heating within the atmosphere; etc.

In order to minimize the thrust required to inject the vehicle into orbit, the exit should be made at a shallow angle. This implies a near full negative lift at the time of exit. Most of the other considerations, noted however, require that the vehicle be flown to steeper exit angles and exit holding near zero lift. Fig. 8 is included to illustrate control results[29] in such a skip-out maneuver. These data show the deviation of the maximum skip-out altitude actually achieved during the skip-out maneuver from the desired parking orbit altitude as a function of density scale height and exit angle error.

As presented on the left side of Fig. 8 the skip-out error for positive scale height variations is found to be minimal. For negative scale height variations, the maximum skip-out altitude may be much higher than that desired because the density decreases with altitude more than expected in the guidance equations; thus the vehicle exits at a somewhat higher velocity than desired. For uncertainties in the density scale height within ±25 percent there is only a small error in the maximum skip-out altitude.

The right side of Fig. 8 shows that an error in flight-path angle directly affects the maximum skip-out height. For the conditions considered there is an error of about 860 meters in the maximum skip-out altitude for each meter per second of vertical velocity error at exit. An error of about 2000 meters in the maximum skip-out altitude is also found for each meter per second of horizontal velocity error at exit. The final maneuver to accelerate the vehicle into the desired orbit can compensate for some of the errors in the skip-out maneuver.

Skip-out range control in Earth entries.- In the skip-out maneuver in Earth entries the considerations of measurement uncertainties and heating are of primary importance. From Fig. 7 it can be seen that the steeper the exit, the less sensitive the range to changes in exit angle. From the heating standpoint it is desirable to decelerate at the lower altitudes and then pull near full positive lift to extend the range. This also implies an exit at steep flight-path angles. An exit angle of about 5°, close to the maximum exit angle that can be achieved for typical entry configurations, appears to be reasonable for extended range control at Earth.

In the skip-out maneuver for extended range, certain exit errors can be compensated for during the second entry. This is illustrated in Fig. 9 where the attainable range during the second entry is presented for various constant L/D trajectories. For nominal skip-out ranges on the order of 15,000 km, an $L/D = 0.4$ vehicle can compensate for skip-out range deviations on the order of ±500 km and an $L/D = 0.8$ vehicle can compensate for skip-out range deviations on the order of ±1,500 km. Range deviations due to representative measurement errors are compared to these ranging capabilities in Fig. 9. These data illustrate that a vehicle with an L/D capability of less than about 0.4 is marginal in its ability to compensate for these typical skip-out errors. An important tradeoff can be inferred from this discussion; that is, more accurate skip-out control is mandatory with lower L/D vehicles, and less accurate skip-out control can be tolerated with higher L/D vehicles. For a vehicle with an $L/D = 1$, exit angle errors up to $\pm 1.5^{\circ}$ or exit velocity errors up to ±60 m/sec can be tolerated and a satisfactory terminal control maneuver can be performed after the skip out.

Terminal range control in Earth entry.- The discussion in this section applies both to the final range control maneuver after the skip out and to the short range control maneuvers from supercircular velocity in which the vehicle is not required to skip out of the atmosphere. The terminal control requirements are to guide the vehicle near to the desired touchdown point with the vehicle in a position to make the final touchdown.

A trajectory is illustrated in Fig. 10 for the control of terminal range by a roll-modulated vehicle.[27] The vehicle makes its range maneuver at a velocity of $\bar{V} = 1.4$ and about 3000 km from the desired destination. This is representative of nonskip range control from supercircular velocity. The vehicle is guided toward an equilibrium glide trajectory which terminates at the desired destination. A trajectory with a roll angle of $\pm 60^{\circ}$, as shown, is near the center of the subcircular downrange capability. A variation in vertical lift force is necessary for the vehicle to fly near this subcircular glide path to its destination. This force determines the magnitude of the roll angle. The sign of the roll angle (i.e., right or left) is determined by the crossrange to the destination. As shown in the figure, the vehicle is allowed to fly to one side until the crossrange exceeds a design envelope at which time the sign of the roll angle is reversed. The design envelope is a converging deadband that represents about one-half of the crossrange capability. The roll-angle history is shown in the figure with three roll reversals corresponding to the crossrange reversal points. With this crossrange control method, the trajectory converges to the destination as shown.

With automatic guidance systems and this type of control technique, the final steering errors are very small, on the order of 1 km. The primary contribution to the over-all final error is the ability of the inertial system to measure the vehicle's position. This navigation error (as opposed to steering error) with present "state-of-the-art" inertial equipment and updating is on the order of 1 km for each 1000 km of range traveled during entry.[37] It should be pointed out that during entry, at altitudes between about 50 and 100 km, a plasma sheath will encompass the vehicle and any updating from the ground may be impossible. Below 50 km guidance information can be relayed to the vehicle to control the final touchdown.

Now the ability of the pilot to perform the terminal range control maneuver is a function of the display information he is given. It was pointed out in Fig. 3 that the control of downrange represents a sixth-order control task. In order for the pilot to control range he must keep in mind six levels of lead information, unless, of course, this information is combined in appropriate display arrangements. Fig. 11 is included to illustrate the maximum expected terminal steering errors associated with various display arrangements that incorporate progressive levels of lead information.[27]

The first arrangement consisted of six separate displays representing measurements of each of the six state variables. Here it is seen that the steering range errors can be as large as 60 km. The range-to-go information in the velocity command display shown next is incorporated (by means of simple guidance logic) into a "velocity-to-fly-to" command. With this display the pilot must interpret five separate levels of information and the maximum error is on the order of 30 km.

In the acceleration command display, shown next, the range and velocity information is incorporated into an "acceleration-to-fly-to" display. With this display the pilot has to interpret four separate levels of information and the maximum terminal steering error is on the order of 5 km.

For either the acceleration rate command, roll angle command, or roll rate command display arrangement, the terminal steering error can be on the order of 1 km. This represents an accuracy as good as that of the fully automatic system.

The pilot's ratings[27] of the various display arrangements with short-period augmentation both in and out are illustrated in Fig. 12. Without stability augmentation the pilot must damp short-period oscillations about the pitch and yaw axes as well as perform the guidance functions about the roll axis.

With short-period stability augmentation in it is seen that display arrangements which give the guidance task to at least a third-order function (i.e., acceleration rate command) are satisfactory for normal operation. Without short-period stability augmentation it is seen that only guidance display arrangements which give a roll rate command are considered satisfactory for normal operation. In this situation the pilot has simply to look at three short-period rate instruments (roll rate, pitch rate, yaw rate) and correct the rates about each axis.

If the on-board computer and precision inertial measuring equipment have not failed during entry and the pilot must control the vehicle (such as with an autopilot failure), it is reasonable to have the pilot fly by the roll rate or roll angle command as would the completely automatic system. If the precision inertial measuring equipment is not operating during entry, however, there is the problem of obtaining navigation measurements. It appears possible, in emergency situations of this type, to use a strapped down roll gyro along with a single strapped down acceleration as measuring devices.[27,28] The gyro (or a view of the outside scene) can indicate to the pilot the horizon roll angle. A display of the acceleration can give relative altitude changes within the atmosphere. With the proper mounting of the accelerometer on the particular vehicle configuration[27] an integration of the accelerometer output can indicate velocity changes, and a second integration can indicate range changes. These types of back-up measurements are expected to give terminal navigation errors on the order of 1 to 3 percent of the entry range as compared to errors on the order of 0.1 percent that are presently expected with more sophisticated inertial measuring units.

CONCLUDING REMARKS

This paper has illustrated several considerations for the guidance and control of space vehicles entering the atmospheres of Earth and Mars.

First, the control at extreme entry velocities requires a large negative aerodynamic force to keep the vehicle within the atmosphere. The uncontrolled dynamics in this situation are highly unstable.

For Earth entry velocities up to 21 km/sec there is approximately a 1-second time interval within which a roll maneuver must be initiated to insure capture without exceeding a 10g limit. When automatic control is used in the capture maneuver, there is essentially no degradation in the usable entry corridor depth. For simple piloted back-up systems, though, successful capture is limited to entry velocity less than about 19.5 km/sec because of the critical timing of the roll maneuver. For entries at Mars, the capture maneuver is less critical, and either the piloted back-up or automatic system can use essentially all of the available corridor depth.

In considering skip-out control to a parking orbit at Mars there is a direct correspondence between system performance and measurement errors. Density scale height uncertainties up to ±25 percent cause essentially no degradation of performance, however.

In the skip-out maneuvers for extended range, certain exit errors can be compensated during the second entry. There is a direct tradeoff between the magnitude of these allowable exit errors and the maximum vehicle L/D.

The final terminal control error with an automatic system is primarily in the navigation error of the initial measuring unit rather than any steering error. With piloted back-up systems, however, both the navigation and steering errors may be sizable. This paper has illustrated the effect of various lead-information displays on the pilot's ability to perform the range control task. It is concluded that displays that give basic velocity and range-to-go information are unsatisfactory for normal operation; whereas displays that include short-period command information are satisfactory.

REFERENCES

(1) Anon., "EMPIRE - A Study of Early Manned Interplanetary Missions," NASA-MSFC Contract 8-5025, Aeronutronic Div. of Ford Motor Co., Pub. U-1951, Dec., 1962.

(2) Himmel, S. C., Dugan, J. F., Jr., Luidens, R. W., and Weber, R. J., "A Study of Manned Nuclear-Rocket Missions to Mars," IAS Paper 61-49.

(3) Anon., "A Study of Early Manned Interplanetary Missions - Final Summary Report," NASA-MSFC Contract NAS 8-5026, General Dynamics/Astronautics, Rep. AOK 63-0001, Jan., 1963.

(4) Anon., "Manned Interplanetary Mission Study - Summary Report - Volume I," NASA-MSFC Contract NAS 8-5024, Lockheed Missiles and Space Co., Rep. 8-32-63, March, 1963.

(5) Jones, A. L., ed., "Manned Mars Landing and Return Mission Study - Final Report," NASA-Ames Research Center, Contract NAS 2-1408, North American Aviation, Inc., Space and Information Div., Rep. SID 64-619, March, 1964.

(6) Sohn, R. L., ed., "Manned Mars Landing and Return Mission," NASA-Ames Research Center, Contract NAS 2-1409, TRW Space Technology Laboratories, Rep. 8572-6011-RV-000, March, 1964.

(7) Anon., "Preliminary Design of a Mars-Mission Earth Reentry Module - Final Report," NASA-MSC Contract NAS 9-1702, Lockheed Missiles and Space Co., Rep. 4-57-69-1, Feb., 1964.

(8) Shopland, D. J., Price, D. A., and Hearne, L. F., "A Configuration for Re-entry From Mars Missions Using Aerobraking," AIAA Paper 64-480.

(9) Wong, T. J., and Anderson, J. L., "A Preliminary Study of Spacecraft for Manned Mars Orbiting and Landing Missions," SAE-ASME National Air Transport and Space Meeting, New York, N. Y., April 27-30, 1964.

(10) Pritchard, Brian E., "Survey of Velocity Requirements and Reentry Flight Mechanics for Manned Mars Missions," AIAA Paper 64-13.

(11) Syvertson, C. A., and Dennis, David H., "Trends in High-Speed Atmospheric Flight," AIAA Paper 64-514.

(12) Sohn, Robert L., "Manned Mars Trips Using Venus Swingby Mode," Proc. AIAA/NASA Third Manned Spaceflight Meeting (Houston, Texas, Nov. 4-6, 1964) pp. 330-338. AIAA Pub. CP-10, 1964.

(13) Chapman, D. R., An Analysis of the Corridor and Guidance Requirements for Supercircular Entry Into Planetary Atmospheres, NASA TR R-55, 1960.

(14) Wingrove, R. C., and Coate, R. E., Piloted Simulator Tests of a Guidance System Which Can Continuously Predict Landing Point of a Low L/D Vehicle During Atmosphere Re-entry, NASA TN D-787, 1961.

(15) Dow, P. C., Jr., Fields, D. P., and Scammell, F. H., "Automatic Re-entry Guidance at Escape Velocity," ARS Preprint 1946-61.

(16) White, Jack A., Foudriat, E. C., and Young, J. W., "Guidance of a Space Vehicle to a Desired Point on the Earth's Surface," Am. Astronaut. Soc. Preprint 61-41.

(17) Foudriat, E. C., and Wingrove, R. C., Guidance and Control During Direct-Descent Parabolic Reentry, NASA TN D-979, 1961.

(18) Young, John W., and Russell, Walter R., Fixed-Base-Simulator Study of Piloted Entries Into the Earth's Atmosphere for a Capsule-Type Vehicle at Parabolic Velocity, NASA TN D-1479, 1962.

(19) Friedenthal, M. J., "Control of Re-entry From Orbit," Transactions of the 7th Symposium on Ballistic Missile and Space Technology (Air Force Systems Command for Aerospace Systems and Aerospace Corp., Los Angeles, Calif., 1962), Vol. II, pp. 33-87.

(20) Wingrove, R. C., A Study of Guidance to Reference Trajectories for Lifting Reentry at Supercircular Velocity, NASA TR R-151, 1963.

(21) Bryant, J. P., and Frank, M. P., "An Automatic Long Range Guidance System for a Vehicle Entering at Parabolic Velocity," IAS Paper 62-87.

(22) Anon., "A Study of Energy Management Techniques for a High Lift Vehicle," General Electric Co., Air Force Systems Command Tech. Doc. Rep. ASD-TDR-62-77, Vols. 1 and 2, June, 1962.

(23) Austin, Robert W., and Ryken, John M., Trajectory Control and Energy Management of Lifting Reentry Vehicles. Vol. 16 of Advances in the Astronautical Sciences, Sept., 1963, pp. 829-866.

(24) Volgenau, E., Boost Glide and Reentry Control, Chapter 11, Guidance and Control of Aerospace Vehicles, McGraw-Hill Book Company, Inc., New York, 1963.

(25) Wingrove, Rodney C., "A Survey of Atmosphere Re-Entry Guidance and Control Methods," IAS Paper 63-86 (AIAA Journal, Vol. 1, No. 9, Sept., 1963, pp. 2019-2029).

(26) Lessing, Henry C., Tunnell, Phillips J., and Coate, Robert E., "Lunar Landing and Long-Range Earth Reentry Guidance by Application of Perturbation Theory," Second Manned Spaceflight Meeting, Dallas, Texas, April 22-24, 1963, pp. 140-150 (AIAA, Dallas, Texas, 1963).

(27) Wingrove, Rodney C., Stinnett, Glen W., and Innis, Robert C., A Study of the Pilot's Ability to Control an Apollo Type Vehicle During Atmosphere Entry, NASA TN D-2467, 1964.

(28) Tannas, Lawrence E., "A Manual Guidance Scheme for Supercircular Entries," Proc. AIAA/NASA Third Manned Spaceflight Meeting (Houston, Texas, Nov. 4-6, 1964) pp. 79-95. AIAA Pub. CP-10, 1964.

(29) Wingrove, Rodney C., "Trajectory Control Problems in the Planetary Entry of Manned Vehicles. Proc. AIAA Entry Technology Conf. (AIAA, Williamsburg and Hampton, Virginia, Oct. 12-14, 1964) pp. 22-33. AIAA CP-9, 1964.

(30) Morth, Raymond, and Speyer, Jason L., "Divergence From Equilibrium Glide Path at Supersatellite Velocities," ARS Journal, Vol. 13, No. 3, March, 1961, pp. 448-450.

(31) Porter, R. F., "The Linearized Long-Period Longitudinal Modes of Aerospace Vehicles in Equilibrium Flight," Air Force Flight Test Center, TN 61-2, Jan., 1961.

(32) Etkin, Bernard, "Longitudinal Dynamics of a Lifting Vehicle in a Circular Orbit," Air Force Office Sci. Res., TN 60-191, Feb., 1960; also, Journal Aerospace Sci., Vol. 28, 1961, pp. 779-788, 832.

(33) Breakwell, John V., Helgustam, Lars F., and Krop, Martin A., "Guidance Phenomena for a Mars Mission," AAS Symposium on Exploration of Mars, Denver, Colorado, June, 1963.

(34) Hanley, Gerald M., and Lyon, Frank J., "The Feasibility of Spacecraft Deceleration by Aerodynamic Braking at the Planet Mars," AIAA Paper 64-479.

(35) Napolin, A. L., and Mendez, J. C., "Target Orbit Selection for Mars Missions Using Aerodynamic Maneuvering," AIAA Paper 64-14.

(36) Finch, Thomas W., "Aerodynamic Braking Trajectories for Planetary Orbit Attainment," AIAA Paper 64-478.

(37) Hansen, Q. Marion, White, John S., and Pang, Albert Y., Study of Inertial Navigation Errors During Reentry to the Earth's Surface, NASA TN D-1772, 1963.

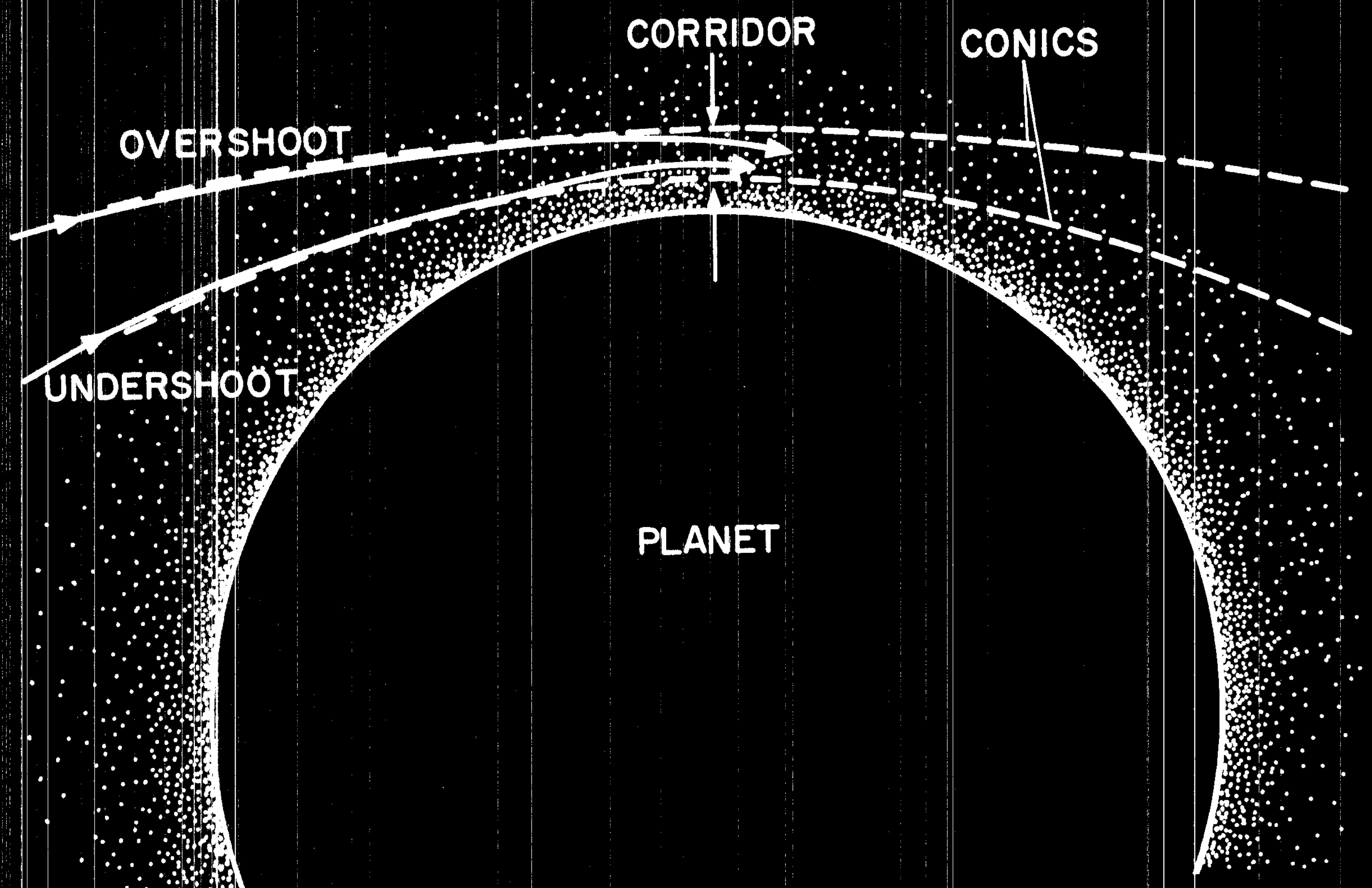

Fig. 1.- Definition of corridor depth.

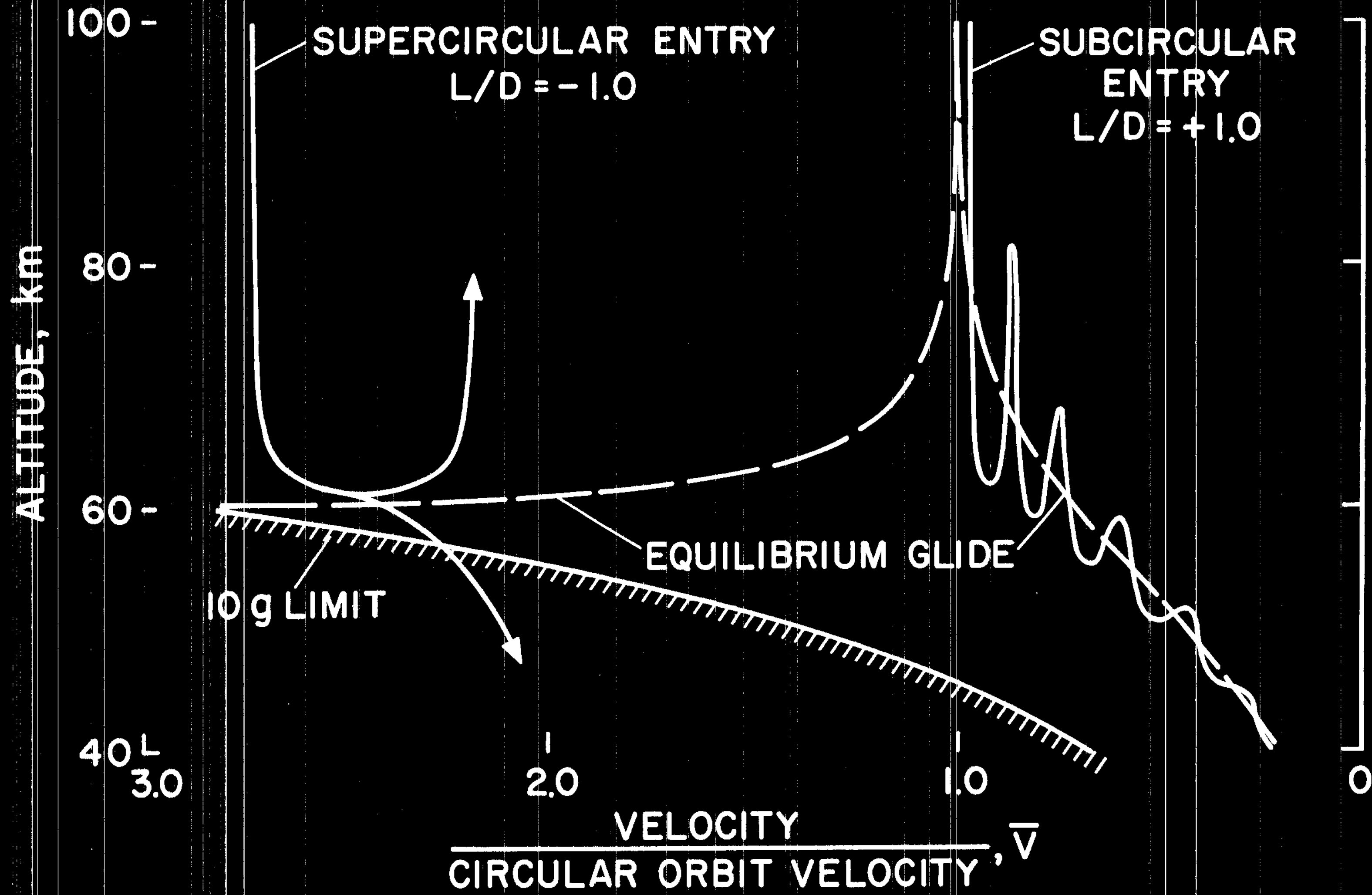

Fig. 2.- Dynamics of constant-trim lifting vehicle in Earth entry.

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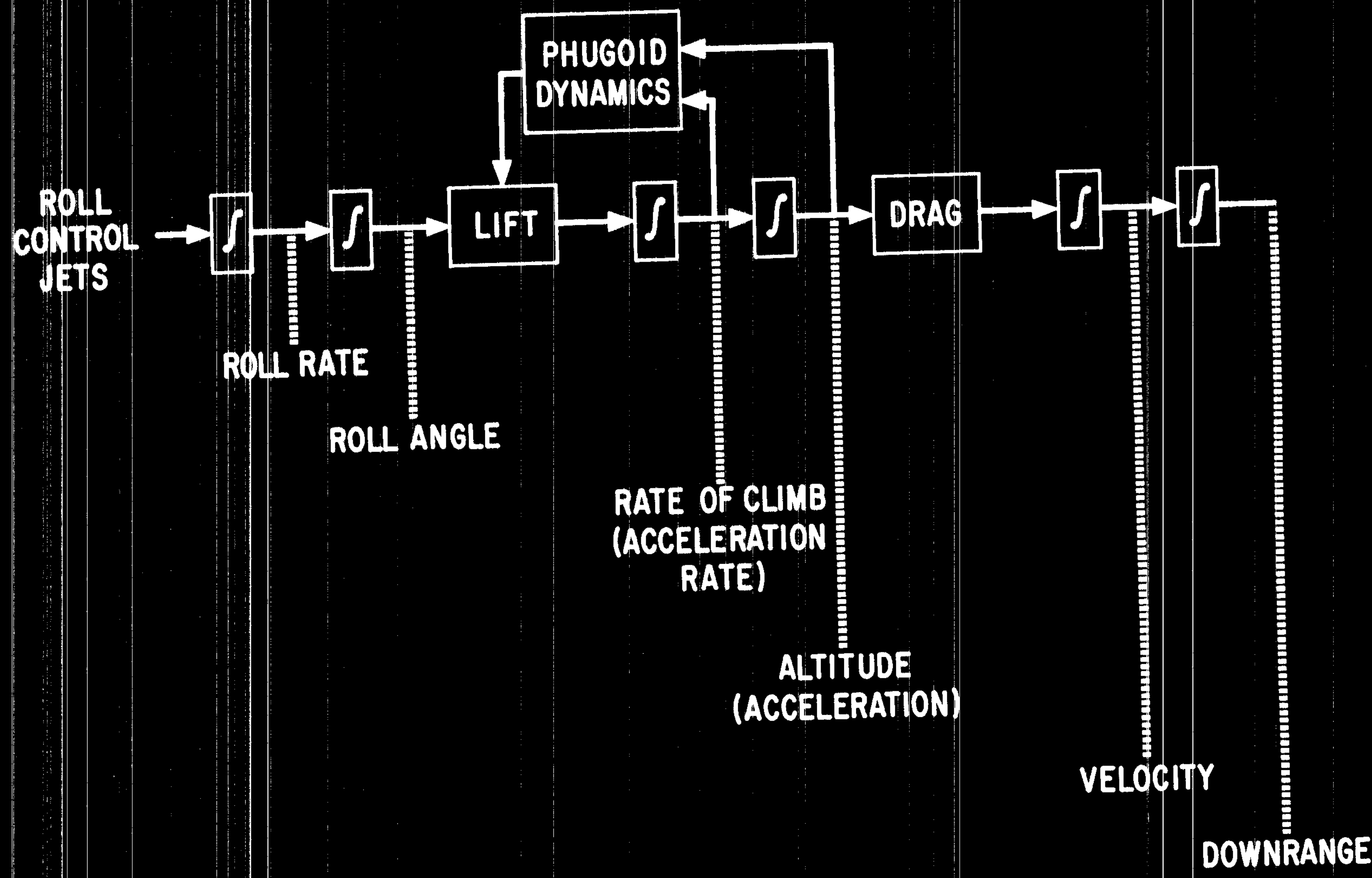

Fig. 3.- Relationship of roll control and trajectory dynamics.

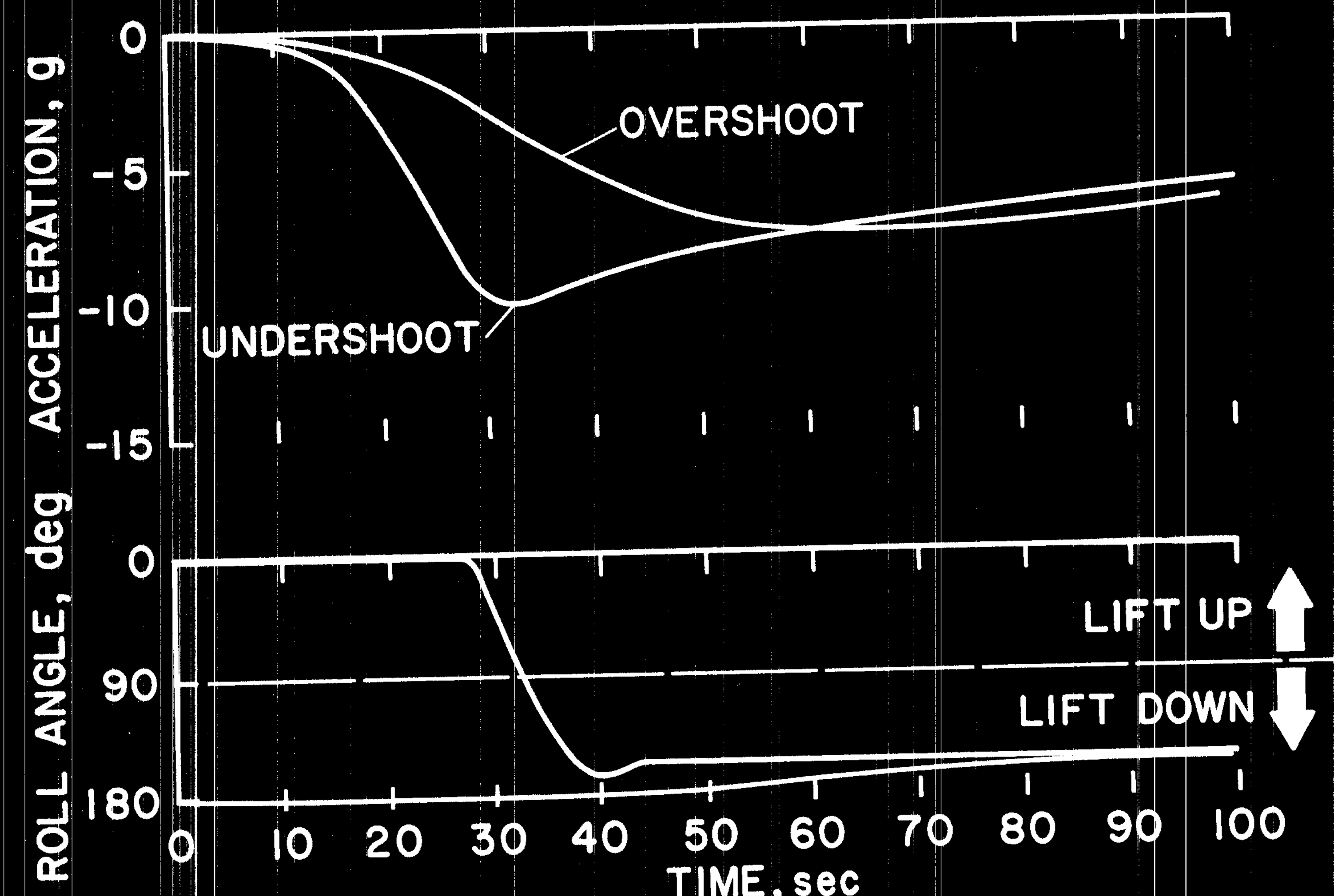

Fig. 4.- Time history of capture maneuvers in Earth entry; maximum L/D = 1, $\overline{V}_i$ = 2.7.

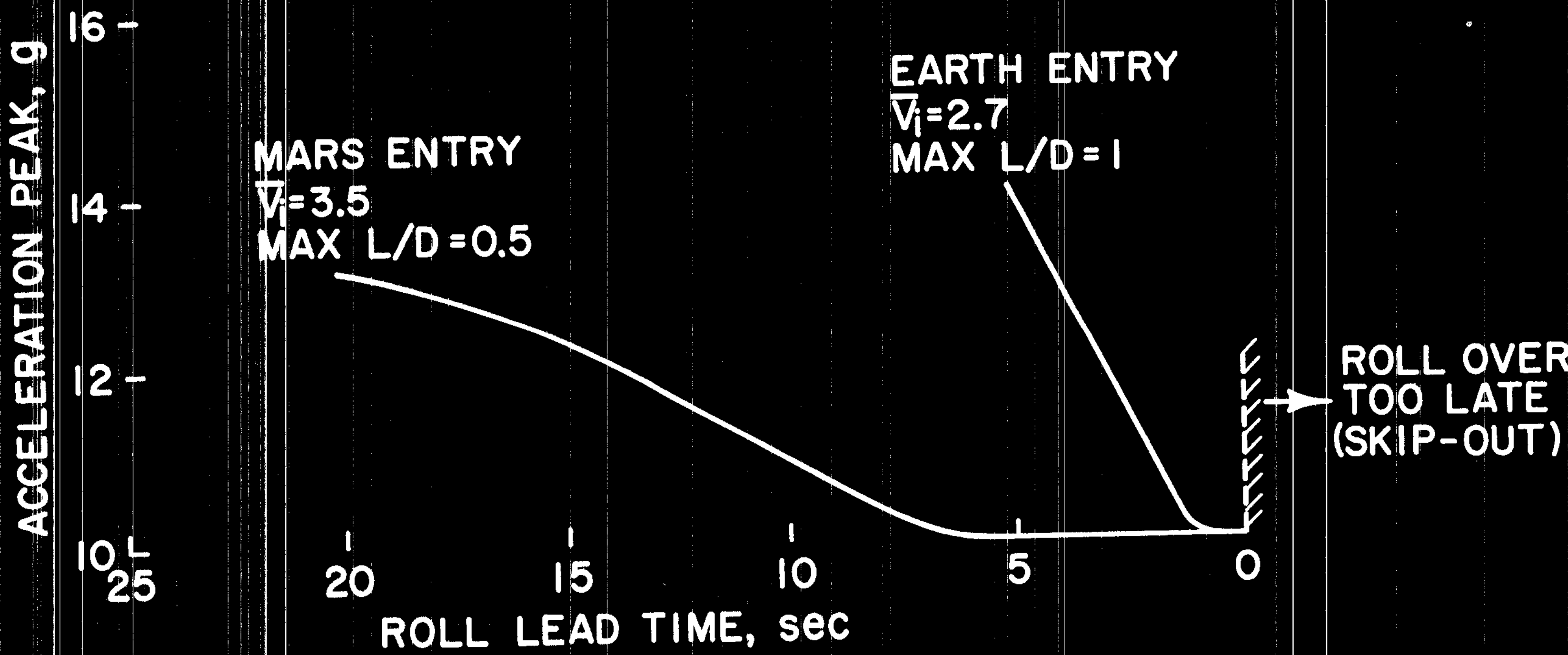

Fig. 5.- Entry at undershoot boundary, maximum roll rate = 20°/sec.

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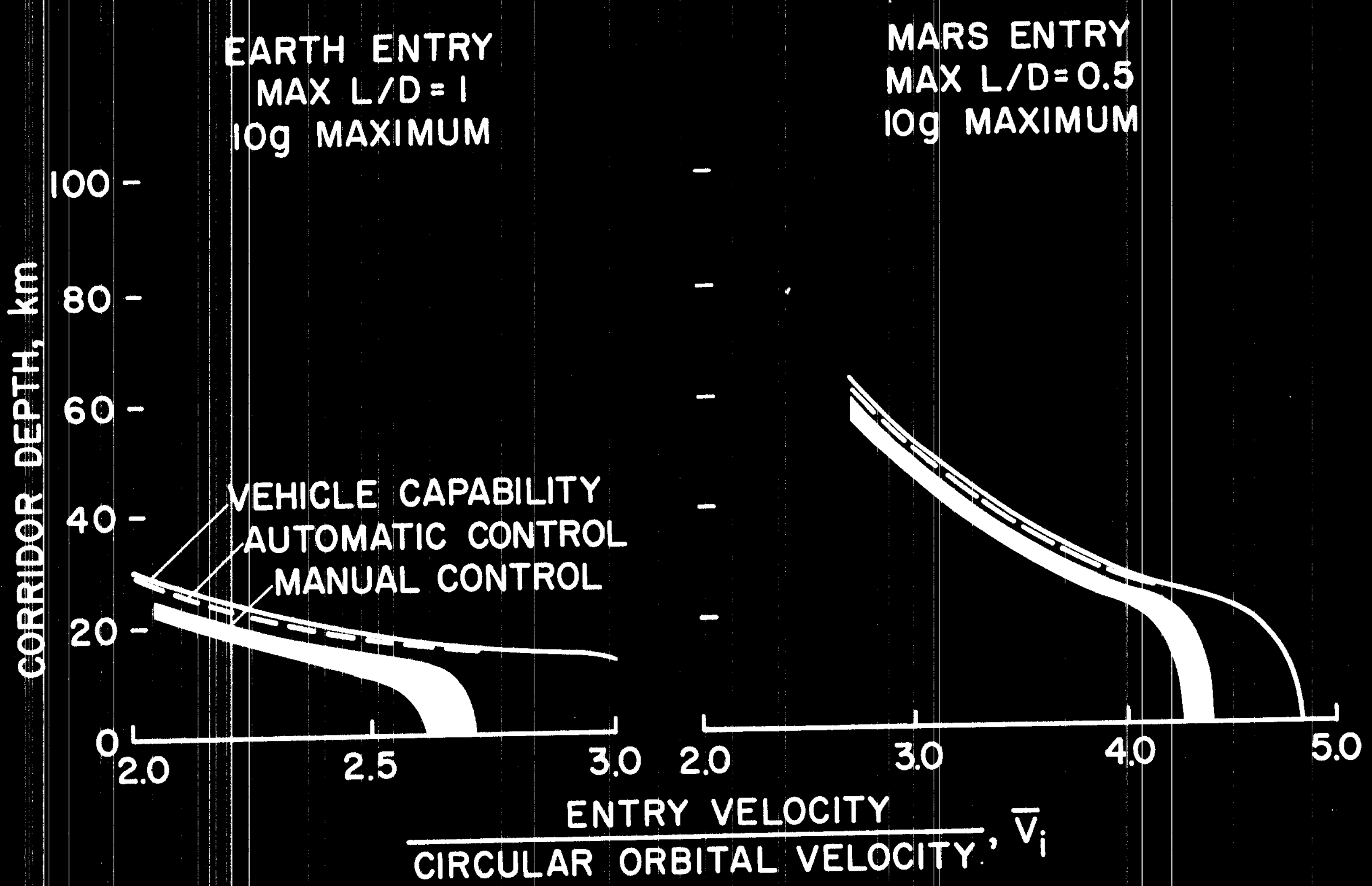

Fig. 6.- Corridor depths as a function of entry velocity.

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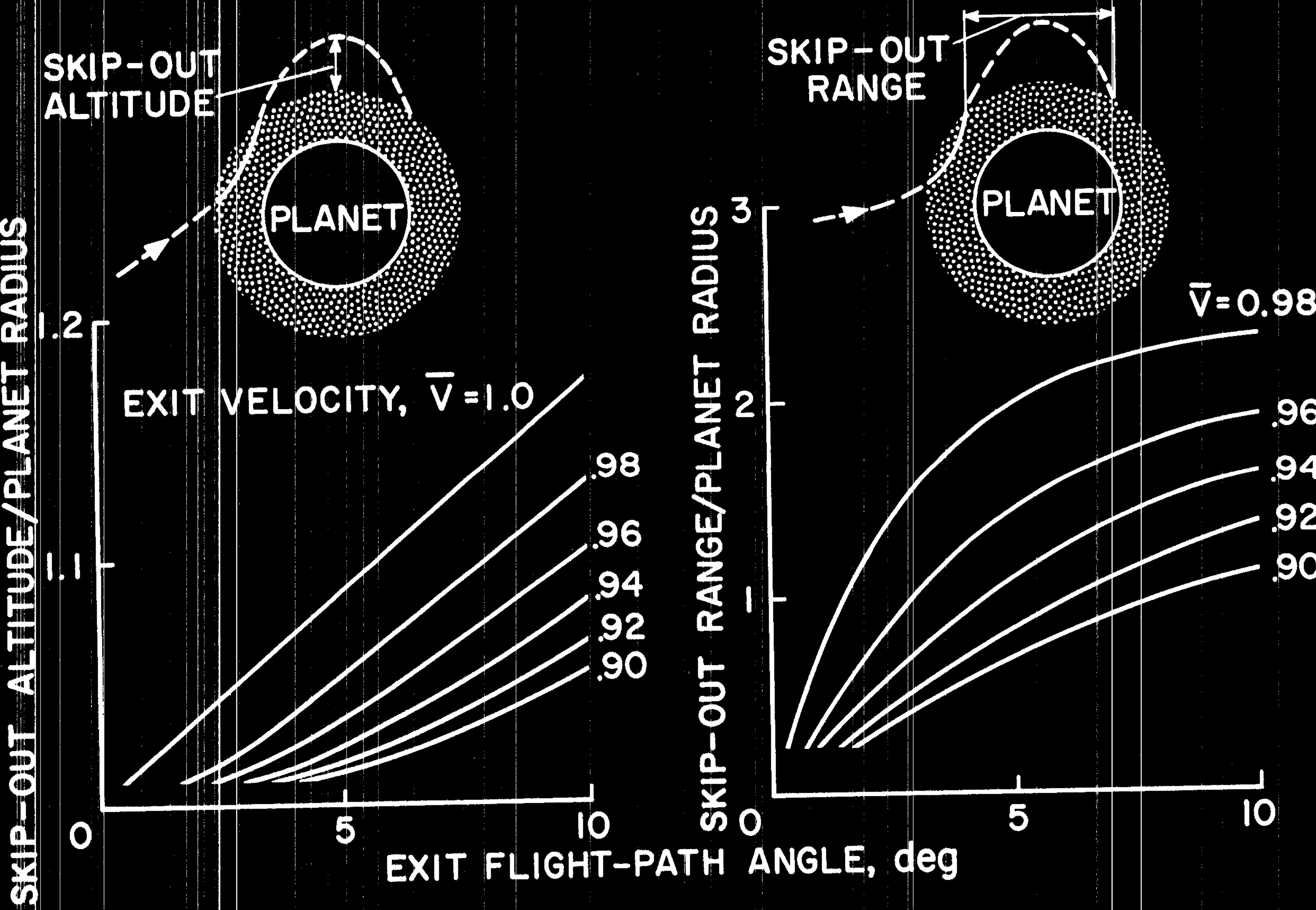

Fig. 7.- The variation of skip-out altitude and skip-out range with exit velocity and exit flight-path angle.

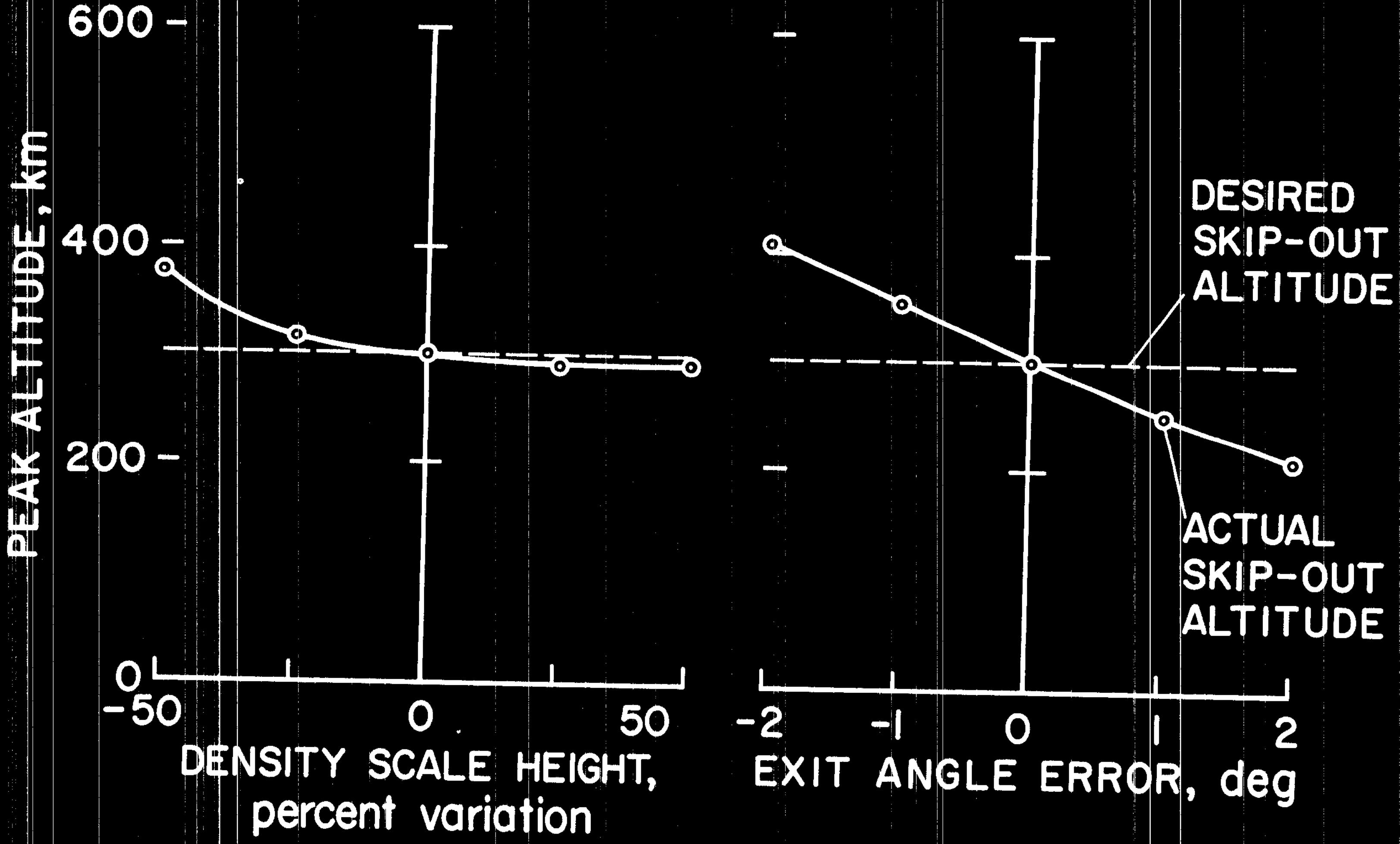

Fig. 8.- Skip-out control at Mars; maximum L/D = 0.5.

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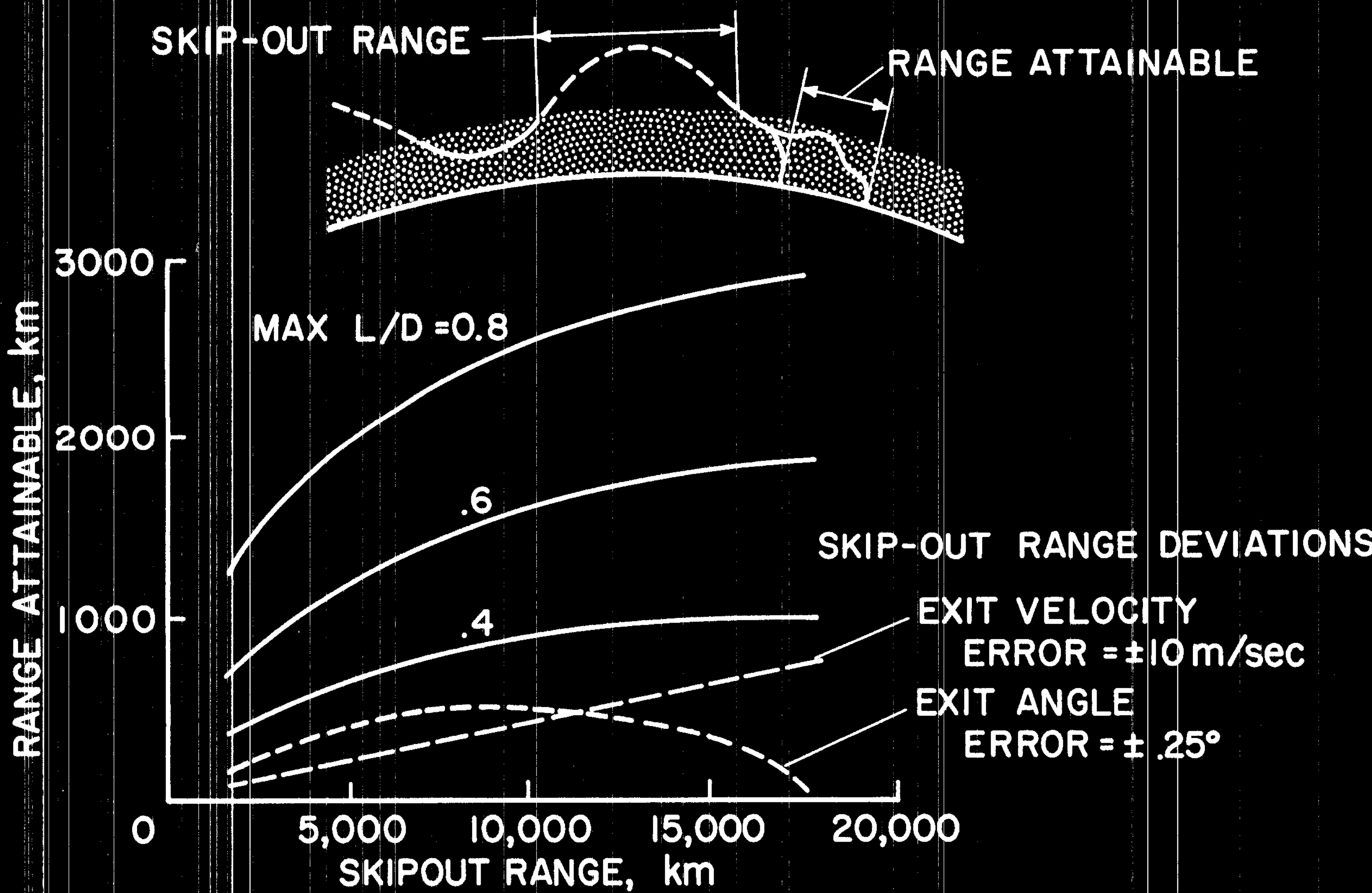

Fig. 9.- Attainable range in the second entry at Earth; exit angle = 5°.

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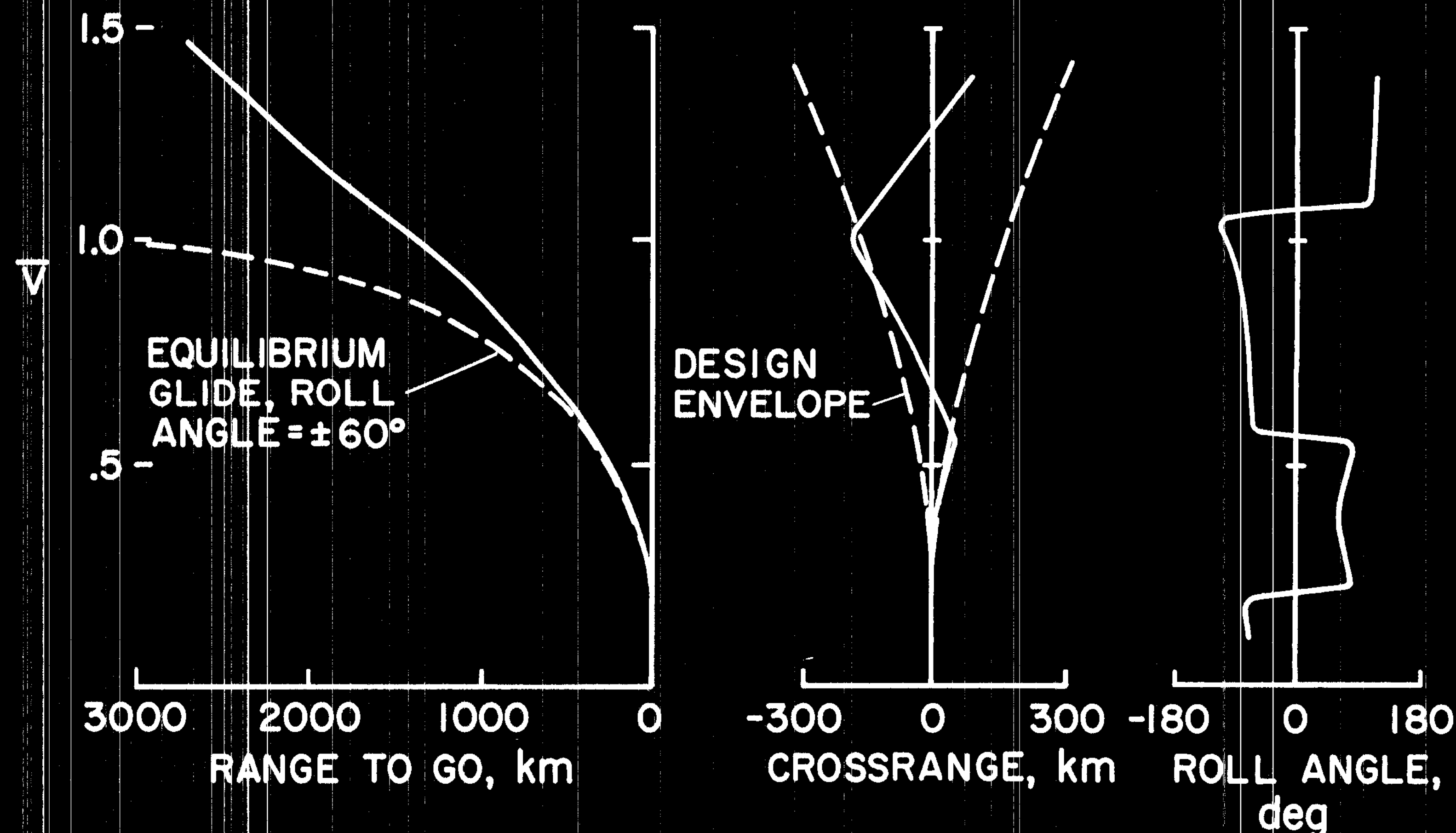

Fig. 10.- Terminal range control with roll modulated vehicle; maximum L/D = 0.5

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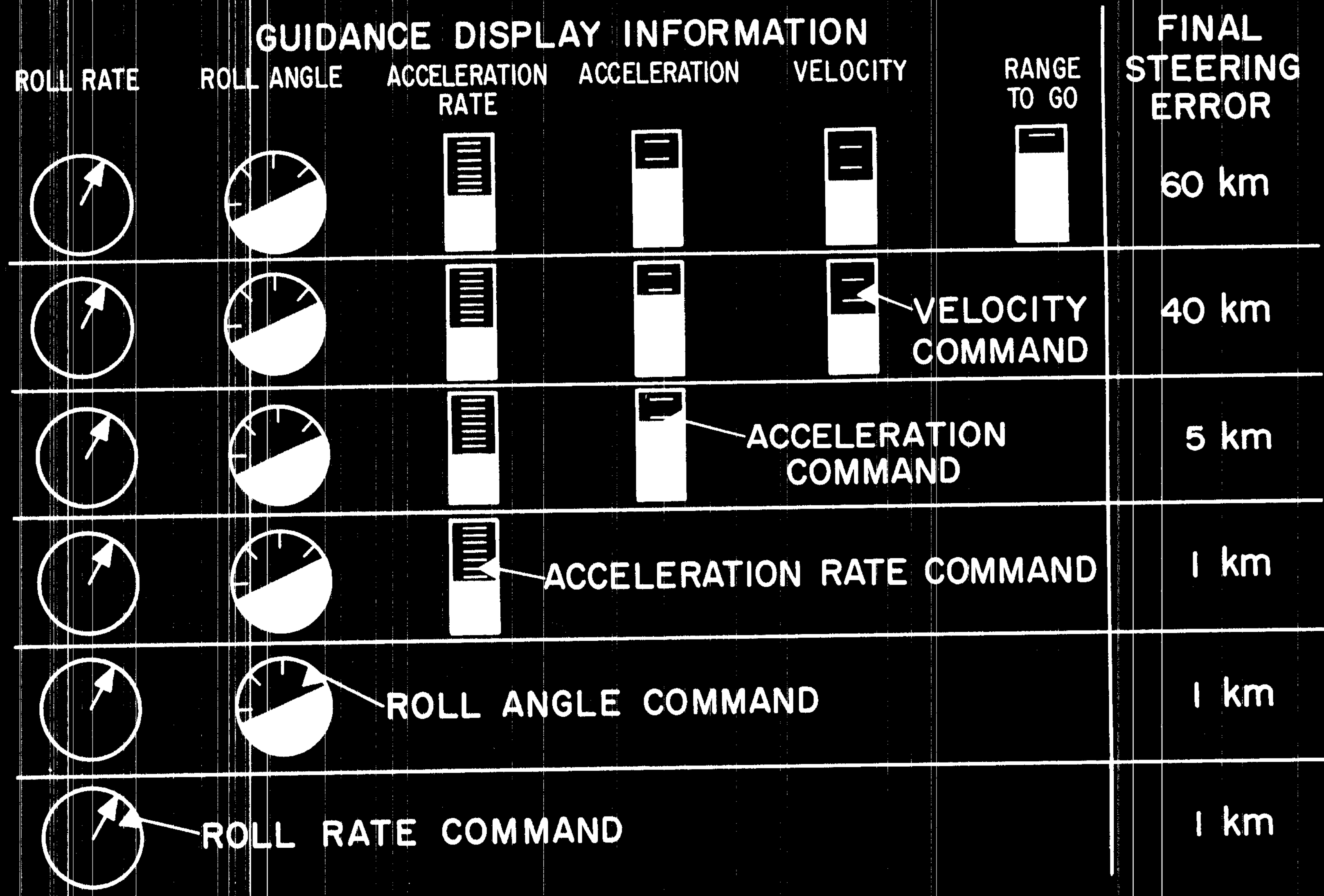

Fig. 11.- Maximum final steering errors for manual control with various levels of guidance display information.

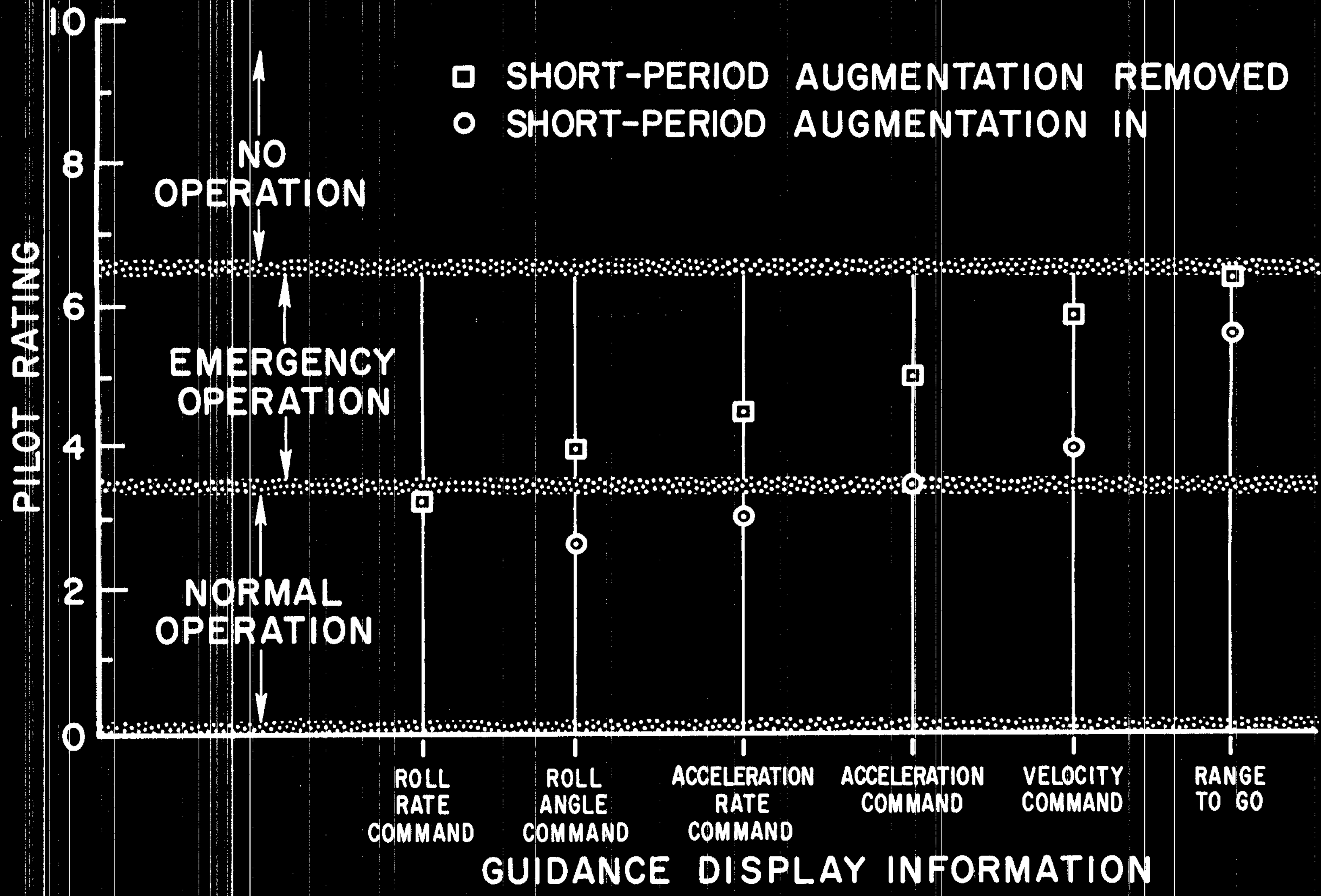

Fig. 12.- Pilot ratings for control with various levels of guidance display information.